

# First results on top-quarks from ATLAS

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The search for first  $t\bar{t}$  candidate events and the related background studies using data-driven techniques are reported for about  $300 \text{ nb}^{-1}$  of  $\sqrt{s}=7 \text{ TeV}$  proton-proton collision data delivered by the Large Hadron Collider (LHC) and collected with the ATLAS detector. Selected events are characterized by the presence of high- $p_T$  isolated charged lepton(s), high jet multiplicity, jet(s) identified as originating from  $b$ -quark by a secondary vertex tagger algorithm, and missing transverse energy. They reveal kinematics properties consistent with top pair production.

## 1. Introduction

During the operation at the center-of-mass energy ( $\sqrt{s}$ ) of 7 TeV, the LHC is expected to deliver up to  $1 \text{ fb}^{-1}$  of  $pp$  collision data by the end of 2011. The top pair production cross section at this energy is expected to be about 160 pb [1], approximately 20 times the corresponding production cross section at the Tevatron collider. Already at this initial stage of the data taking with the ATLAS experiment [2], and with very small data samples, corresponding to an integrated luminosity of  $(295 \pm 32) \text{ nb}^{-1}$ , top pair candidate events are searched for, and preliminary data-driven background studies are carried out. After a short presentation of the key ingredients to top-quark physics analysis, provided in Section 2, early results are discussed in Section 3 and Section 4.

## 2. Ingredients to top-physics: datasets and object selection

Top pair final states are classified according to the  $W$  boson decays. The all-jet mode accounts for about 46% of the decays, and lepton plus jets and dilepton modes for about 44% and 10% of the decays respectively. Final states containing electrons or muons are of particular interest for early measurements as they provide clear trigger signals and rich event signatures. The events contain jets (two of which originate from  $b$ -quarks), high  $p_T$ , isolated charged lepton(s), and missing transverse energy,  $E_T^{\text{miss}}$ , from the escaping neutrino, and explore the complete detector capabilities.

During the initial data taking period only the first of the three level trigger architecture functionalities available in ATLAS have been exploited, allowing for the commissioning of the higher level trigger algorithms and infrastructure. The datasets used for the analysis presented in this paper correspond to an integrated luminosity of  $(295 \pm 32) \text{ nb}^{-1}$ , and have been collected with electron or muon triggers, requiring localized energy deposits in the electromagnetic (EM) calorimeters exceeding a 10 GeV threshold, or hit patterns in the muon spectrometer consistent with muons with  $p_T > 10 \text{ GeV}$  originating from the interaction point. In addition, early data collected using minimum bias triggers, requiring coincidence with bunch crossing of scintillators signals at both detector sides, and jet based triggers, have been used to study and validate physics objects identification and reconstruction recipes, and the corresponding Monte Carlo descriptions [3–10].

Electron candidates are required to fulfill the medium electron definition [3], which in addition to minimal track quality and hits requirements and electromagnetic shower shape information, adopts cluster-to-track matching criteria. Electron candidates must have  $p_T > 20 \text{ GeV}$ , and be within the good detector acceptance ( $|\eta| < 2.47$ , excluding the calorimeter transition region  $1.37 < |\eta| < 1.52$ ). To remove photon conversions, the corresponding track must have an associated hit in the innermost pixel layer (b-layer hit requirement). To reduce the jet mis-identification rate and contributions from heavy flavor decays inside jets, the candidates are required to be isolated: the energy deposition in the calorimeter within a cone of radius  $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.2$  must be less than  $4 \text{ GeV} + 0.023 \cdot p_T^{\text{ele}}$ .

Muons are reconstructed by combining tracks from the inner detector and the muon spectrometer as defined in [4]. Candidate muons are required to have  $p_T > 20 \text{ GeV}$  and  $|\eta| < 2.5$ . To ensure isolation, the energy deposition in the

calorimeter, and the sum of track transverse momenta measured in a cone of radius  $R = 0.3$  around the muon track, are each required to be less than 4 GeV. Additionally, the minimum separation between muons and selected jets is required to be  $R = 0.4$ .

Electron and muon reconstruction and identification procedures have been successfully exploited for the first ATLAS measurements of the  $W$  and  $Z$  production cross sections at the LHC reported in [5, 6].

Jets are reconstructed using the anti- $k_T$  algorithm with  $R$  parameter of 0.4, combining topological clusters in the calorimeters. The latter are obtained as three-dimensional groups of noise-suppressed calorimeter cells, meant to follow the shower development. To avoid double-counting, jets overlapping with selected electrons within  $\Delta R = 0.2$  are vetoed. Due to the non-compensating nature of the ATLAS calorimeter systems, energy scale corrections are needed. Within the initial baseline jet correction scheme, jets are calibrated to the hadronic energy scale using  $p_T$  and  $\eta$  dependent correction factors obtained from simulation [7]. The associated jet energy scale (JES) uncertainty has been evaluated using Monte Carlo events simulated with different detector configurations and hadronic shower models, and comparing the relative data to Monte Carlo response in various detector regions [8]. The total relative JES uncertainty ranges from 8% (9%) in the barrel (end-cap) region for jet  $p_T < 60$  GeV, to 6% (7%) for higher  $p_T$  jets. The main contributions to the uncertainties originate from imperfect dead material knowledge (5%), from shower modeling and noise description (3-4)%, and from the absolute energy scale of the calorimeter (3%).

The  $E_T^{\text{miss}}$  [9], complementing the lepton identification in selecting genuine  $W \rightarrow l\nu$  decays, is reconstructed from the vector sum of all calorimeter cells, resolved into the transverse plane. Cells not associated to a jet or electron are included at the electromagnetic scale, *i.e.* without correcting for non-compensating calorimeter effects. Cells associated with jets are subject to the calibration scheme described above. Finally, additional  $E_T^{\text{miss}}$  refinements based on information from reconstructed leptons ( $e/\mu$ ) are applied.

The identification of jets originating from  $b$ -quarks constitutes an effective handle to reject backgrounds to  $t\bar{t}$  events. Currently, the default  $b$ -tagging algorithm is based on the explicit reconstruction of secondary vertices within jets, using tracks displaced with respect to the primary vertex. The tag is assigned using the secondary vertex decay length significance,  $L/\sigma(L)$ , corresponding to a  $b$ -jet identification efficiency of 50%, as evaluated from simulated  $t\bar{t}$  Monte Carlo events [10].

### 3. Search for first top-quark pair candidate events

A search has been performed for events consistent with top-quark pair production in  $(295 \pm 32)$  nb $^{-1}$  of 7 TeV  $pp$  collision data recorded by ATLAS between the end of March and mid-July 2010 [11].

The selection of both lepton plus jets and dilepton  $t\bar{t}$  candidates starts from events collected by single lepton ( $e/\mu$ ,  $p_T > 10$  GeV) level-one triggers. Events must have a reconstructed primary vertex with at least 5 tracks, and are discarded if they contain any jet consistent with out-of-time activity or calorimeter noise.

The selection of lepton plus jets  $t\bar{t}$  events requires the presence of exactly one offline-reconstructed electron or muon with  $p_T > 20$  GeV. At least four jets with  $p_T > 20$  GeV and  $|\eta| < 2.5$  are then required, at least one of which must be  $b$ -tagged. Finally, the  $E_T^{\text{miss}}$  is required to be above 20 GeV. For background studies in data control samples, the event selection is modified to accept events with one or more jets, with and without  $b$ -tagging requirements.

The selection of dilepton  $t\bar{t}$  candidates shares the same baseline object definition as for the lepton plus jets channel, however, the requirements on the number of selected jets is relaxed to at least two, and no  $b$ -tagging is required. Two oppositely-charged leptons ( $ee$ ,  $\mu\mu$ , or  $e\mu$ ) each satisfying  $p_T > 20$  GeV are required. In the  $ee$  channel, to suppress backgrounds from Drell-Yan and QCD multi-jet events, the missing transverse energy must satisfy  $E_T^{\text{miss}} > 40$  GeV, and the dilepton invariant mass must be at least 5 GeV away from the  $Z$  boson mass, *i.e.*  $|m_{ee} - m_Z| > 5$  GeV. For the di-muon channel, the corresponding requirements are  $E_T^{\text{miss}} > 30$  GeV and  $|m_{\mu\mu} - m_Z| > 10$  GeV. For the  $e\mu$  channel, where the background from  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  is expected to be much smaller, no  $E_T^{\text{miss}}$  or  $Z$ -mass veto cuts are applied, but the event  $H_T$ , defined as the scalar sum of the transverse energies of the two leptons and all the selected jets, must be above 150 GeV.

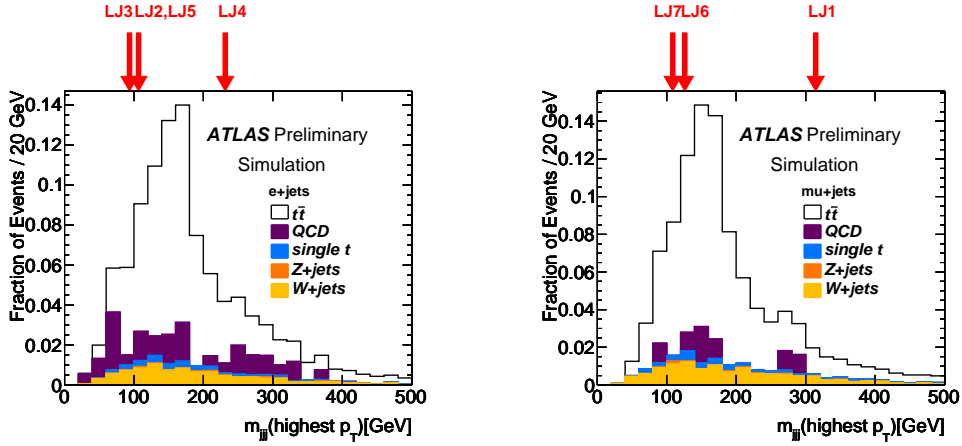


Figure 1: Invariant mass of the 3-jet combination having the highest  $p_T$  for events passing the electron (left) and muon (right) plus jets  $t\bar{t}$  selection.

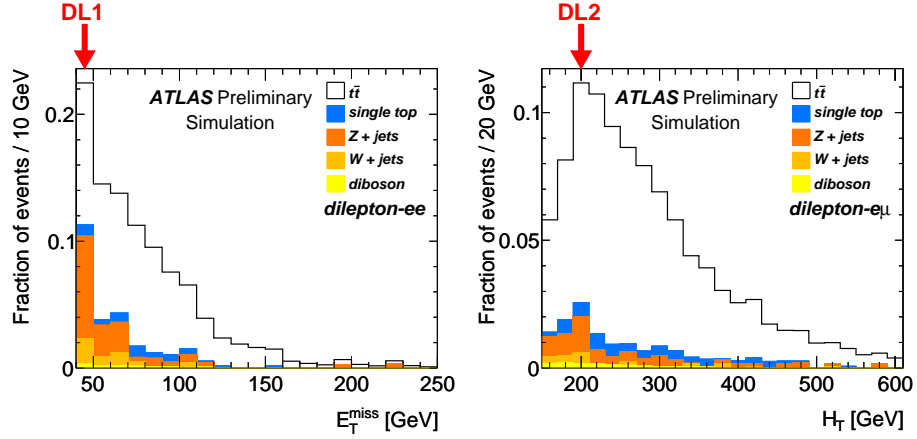


Figure 2: Left (Right): Distribution of the  $E_T^{\text{miss}}$  ( $H_T$ ) for events passing the  $ee$  ( $e\mu$ ) dilepton event selection.

The distributions of the invariant mass of the 3-jet combination having the highest  $p_T$ ,  $m_{jjj}$ , for events passing the electron (muon) plus jets selection is reported on the left (right) of Fig. 1. The total histogram is normalized to unit area, and the relative signal and background contributions are from Monte Carlo expectations. Similarly, Fig. 2 reports the expected  $E_T^{\text{miss}}$  and  $H_T$  distributions for events surviving the  $ee$  and  $e\mu$  dilepton selections, respectively. In both figures, the red arrows indicate the corresponding values of the selected top candidates in the data. In the  $(295 \pm 32) \text{ nb}^{-1}$  dataset, no  $\mu\mu$  dilepton candidate has been observed.

Selected ATLAS event displays for candidates in the lepton plus jets and dilepton channels are provided in Fig. 3. An electron plus jets event is shown on the left: the electron ( $p_T = 41 \text{ GeV}$ ) is depicted as the orange downward-pointing track associated to the green cluster, and as the green tower in the  $\eta - \phi$  plane lego plot. The direction of the missing transverse energy ( $E_T^{\text{miss}} = 89 \text{ GeV}$ ) is shown as the dotted line in the  $r - \phi$  view. The event contains four jets with  $p_T > 20 \text{ GeV}$ , and has an  $m_{jjj}$  of 106 GeV. Fig. 3 displays on the right an  $e\mu$  dilepton candidate. The isolated muon ( $p_T = 48 \text{ GeV}$ ) is shown in red, the isolated electron ( $p_T = 23 \text{ GeV}$ ) is reported as a red track pointing to a green cluster. In the  $\eta - \phi$  plane lego plot, the  $b$ -tagged jet is marked as a blue circle, while the direction of the missing transverse energy ( $E_T^{\text{miss}} = 77 \text{ GeV}$ ) is shown as a white dashed line. Finally, the zoom into the primary vertex region allows to appreciate three displaced blue tracks associated to a secondary vertex tagged jet. The event

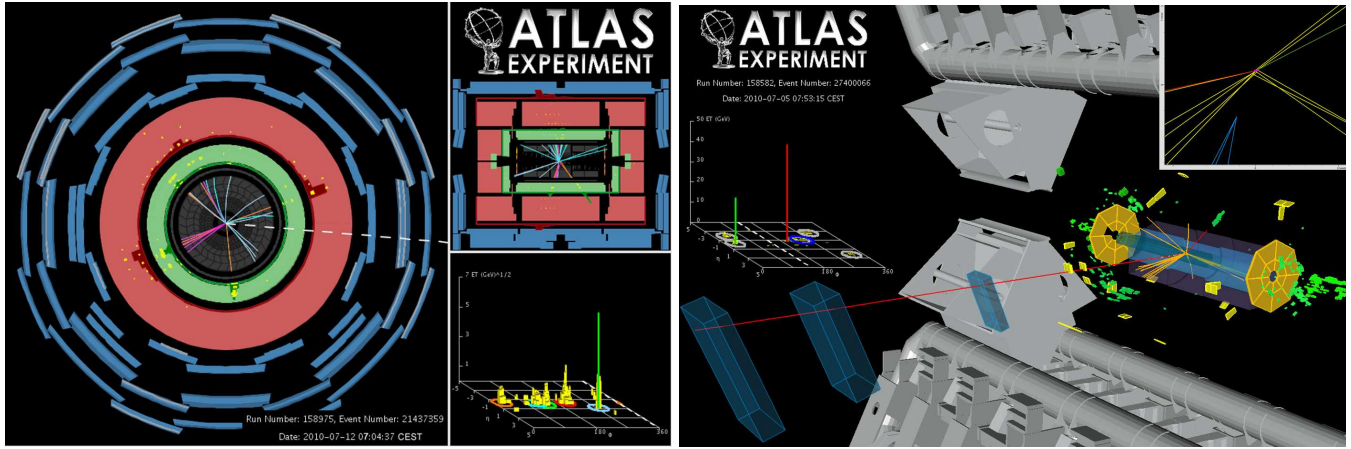


Figure 3: Event displays for selected candidate events. Shown are on the left an  $e$ +jets candidate and on the right a  $e\mu$  dilepton candidate. See text for details.

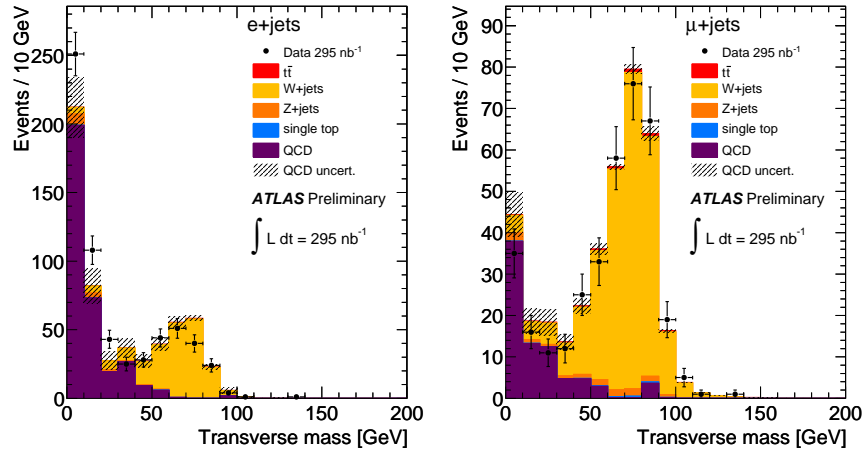


Figure 4: Distribution of the transverse mass of the  $W$  boson for the modified lepton plus jets selection requiring at least one jet with  $p_T > 20$  GeV. The data shown by the points with error bars are compared to the sum of all expected contributions, taken from Monte Carlo simulation or estimated using a data-driven technique (QCD multi-jet). The hatched area shows the uncertainty on the total expectation due to the statistical error on the QCD background estimate.

has  $H_T = 196$  GeV.

#### 4. Background studies

In parallel to the selection of top-like events, careful studies of the background contamination in the selected samples constitute an essential step in measuring the top pair production rate in ATLAS. The lepton plus jets channel in particular suffers from significant background contributions from other Standard Model processes such as the production of  $W$  bosons in association with multiple jets ( $W$ +jets), and QCD multi-jet events. In general these background contributions are difficult to model reliably using Monte Carlo information alone, so that data-driven techniques for their estimate are preferable. The  $W$ +jets background to the signal region ( $N_{jet} \geq 4$ ) can be constrained by using lower jet multiplicity events, with and without  $b$ -tagging requirements. On the other hand the

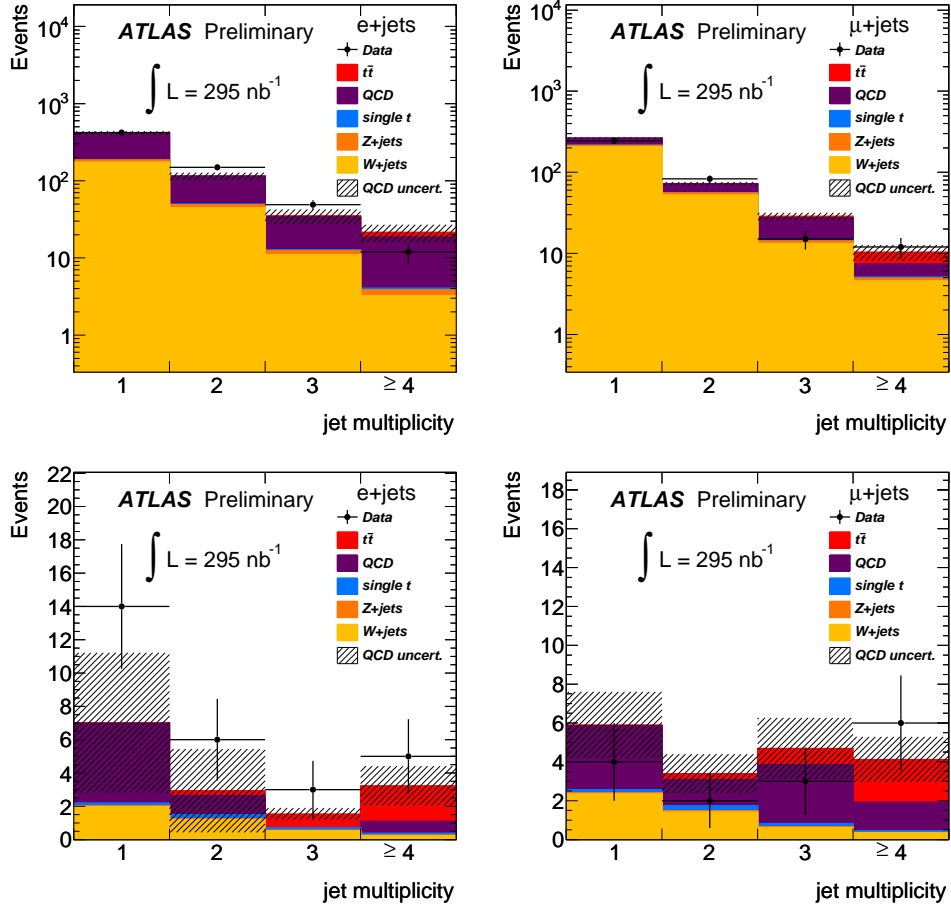


Figure 5: Jet multiplicity distributions for the modified lepton plus jets selection without (top) and with (bottom)  $b$ -tagging requirements.

QCD multi-jet background can be studied using background-enhanced control samples, in low jet multiplicity bins and low  $E_T^{\text{miss}}$  regions.

Currently the data-driven QCD estimate in the lepton plus jet channel is obtained from the matrix-method technique [12]. This approach is based on the definition of two data regions characterized by a tight and a loose lepton definition. The data surviving the loose and tight lepton selections are interpreted as the sum of the contributions from events with real ( $\epsilon_{\text{real}}$ ) and fake leptons ( $\epsilon_{\text{fake}}$ ). By knowing the efficiencies for a real ( $\epsilon_{\text{real}}$ ) and fake ( $\epsilon_{\text{fake}}$ ) loose lepton to fulfill the tight selection, the number of  $W$ -like (including  $t\bar{t}$ ) and QCD events can be derived. In the current implementation the tight lepton definitions follow the object requirements described above, while the loose definitions drop the  $b$ -layer hit or the isolation requirements for electrons and muons respectively. The  $\epsilon_{\text{real}}$  is derived from simulated  $Z$  decays, while  $\epsilon_{\text{fake}}$  is determined from a QCD enhanced sample obtained by requiring the presence of at least one jet above 20 GeV and  $E_T^{\text{miss}} < 10$  GeV. To account for possible  $W$ -like contaminations in the control sample an iterative correction procedure is applied.

The transverse  $W$  boson mass in events fulfilling a modified lepton plus jets selection, requiring at least one jet with  $p_T > 20$  GeV and no  $b$ -tagging is shown in Fig. 4 for  $e$ +jets and  $\mu$ +jets events, respectively. The QCD contribution is obtained from the matrix-method described above. All other contributions are taken from Monte Carlo expectations. The hatched area shows the uncertainty on the total expectation due to the statistical uncertainty on the QCD background estimate. The good agreement between data and Monte Carlo provides confidence in the ability to correctly predict both the normalization and the shape of the QCD multi-jet background with the matrix-method.

The jet multiplicity distributions for events satisfying the modified selections are shown in Fig. 5, before (top row)

and after (bottom row)  $b$ -tagging. The un-tagged distributions show that significant samples of  $W+1,2$  jets events are becoming available, to allow the simulation predictions in the  $\geq 4$ -jet bin to be constrained with the data. Overall, the data to Monte Carlo agreement is remarkable also after  $b$ -tagging (bottom row), when, despite the low statistics, the high jet multiplicity data starts to reveal contributions consistent with  $t\bar{t}$  production.

## 5. Conclusions

All ingredients needed for top-physics analysis are currently available in ATLAS: reconstruction of leptons, jets and  $E_{\text{T}}^{\text{miss}}$  as well as  $b$ -tagging tools are in a well advanced commissioning stage. In all aspects, current performances studies, based on early  $pp$  collisions at  $\sqrt{s}=7$  TeV, reveal an overall good data to Monte Carlo agreement, reflecting the maturity of the detector understanding, and the readiness of the ATLAS experiment to reconstruct complex final states as those stemming from  $t\bar{t}$  production.

A search for first top candidates in  $(295 \pm 32) \text{ nb}^{-1}$  has been reported, and several events with kinematic properties consistent with the  $t\bar{t}$  production, in both the lepton plus jets and dilepton topologies have been observed and investigated. In the lepton plus jet channel preliminary data-driven techniques have been applied for the determination of the QCD multi-jet contribution to the selected data sample, which in addition contains significant numbers of  $W+1,2$  jets events that will shortly allow the Monte Carlo predictions for  $W$ +jets background to be constrained by the data.

Although larger data samples will be required to quantify backgrounds to a level that can support a conclusive top quark observation in ATLAS, current results are very encouraging and demonstrate the readiness of the ATLAS collaboration to conduct its top-quark physics program.

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